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July 1977

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A monolithic zinc-oxide-on-silicon p-n storage correlator has been constructed. When operated both as a convolver and as a storage correlator, the electronic efficiency obtained with this device is comparable to that of the present $LiNbO_3$ airgap devices. This device has the potential of having very large dynamic range because of the absence of spurious bulk wave generation, as occurs in the airgap device. Several signal processing functions have been demonstrated with this new type of storage correlator. In one chirp correlation experiment, correlation of signals with a time-bandwidth product of 4000 has been observed.

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ACOUSTICALLY SCANNED OPTICAL IMAGING DEVICES

SUMMARY

During the last six months, a great deal of progress has been made in the development of our surface acoustic wave convolver device. The main effort has been devoted to the development of the surface acoustic wave correlator, because of its basic importance to all kinds of signal processing and, eventually, to imaging, because of the very high sensitivites that are available in this mode of operation.

The two major breakthroughs are; that a complete theory of the surface acoustic wave storage correlator has been developed and checked experimentally on our airgap correlator devices. This theory predicts the behavior of the device with input amplitudes, time of the input signals, the amplitude of the readout signals, and with the physical parameters of either p-n diodes or Schottky diodes that are employed. The theory has been checked, not only on our own experimental devices but also on the Lincoln Laboratory results obtained with Schottky diode devices. In all respects where it can be checked, the results appear to be accurate within a few dB's, and all the experimental parameters vary quantitatively in the same way as the predicted theory. When they can be checked in other cases, the qualitative variation is exactly of the type that would be predicted. Thus, we have a complete design procedure for these storage correlator devices available, which predicts that their efficiency is very close to that of a similar device used as a convolver, as is the dynamic range. This implies that such devices, when feedthrough can be kept at a sufficiently low level, should have a dynamic range of the order of 60 dB's . The experimental results check well with this hypothesis.

The second major result is that we now have the ZnO on Si technology,

a greatly improved condition. We have made the first ZnO on Si storage correlator and have tested several of them. The transducer efficiency of these devices now varies from run to run by only 1 - 2 dB's. The correlation efficiency varies by as much as 10 dB's , but this is because we have been varying the substrate temperature during the ZnO deposition in different runs to try and obtain an optimum value. We have found that, by lowering the deposition rates and optimizing the temperature, we obtain the best quality ZnO . In this case, we obtain the best correlation efficiencies.

We have found that the ZnO on Si monolithic device has certain major advantages over that of the equivalent airgap device. The primary advantage is that, because of the thin piezoelectric film employed, there is no excitation of bulk waves. Therefore, there is no feedthrough problem associated with bulk waves on readout; a major difficulty of the airgap device. By paying extremely careful attention to shielding, we have also eliminated the capacitive feedthrough in these devices to below the thermal noise level. Initially, it was not clear that it could be done with this configuration. The results obtained are better than we could have hoped for. The only remaining feedthrough problem is associated with some surface wave excitation. We are very confident that we can eliminate this because we believe it is associated with an incorrect choice in the diode configuration; one which uses a mask with staggered diodes was primarily employed for historical reasons because this particular mask was available and seemed convenient to use. We are changing the mask and believe that the surface wave problem should be eliminated so that, under all condictions, we will obtain a full dynamic range of the devices,

i.e., 60 dB's.

We have tested the device and shown that it correlates Barker codes well, as it does with FM chirp signals. In this mode, we can correlate a chirp signal read into the device and stored in it with a later chirp signal read into the device.

We have also tested an entirely new mode of operation, which we believe to be of great importance. This involves using the correct signal level so that we can insert two extremely long signals into the device within the storage time of the device and correlate them with each other. The maximum time bandwidth of this correlation process should be determined by the storage time of the device and the bandwidth of the transducers. We have carried out such experiments both in the airgap and the ZnO on Si device. In one experiment on the ZnO on Si device, we have correlated two signals with a time bandwidth product of 4000, corresponding to 700 μsec chirps with a bandwidth of 6 MHz. This, as far as we know, is at least a factor of 5 larger than has been done before in any surface wave device. In the end, we believe this process can lead to correlation of signals with hundreds of milliseconds long and bandwidths in the range of 20 - 100 MHz. This leads to possible correlation time bandwidth products as large as 10^6, or more. Limitation here will be no more to the dynamic range of the system than the time or bandwidth.

We enclose, for the rest of the report, three papers that have been submitted for publication in Applied Physics Letters and Electronics Letters. In addition, we are submitting material on this work to the Ultrasonics Symposium, and we are writing a long paper on the details of the new theory which predicts most of these effects in detail.

A MONOLITHIC ZINC-OXIDE-ON-SILICON P-N DIODE STORAGE CORRELATOR*

by

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ABSTRACT

A monolithic zinc-oxide-on-silicon p-n storage correlator has been constructed. When operated both as a convolver and as a storage correlator, the electronic efficiency obtained with this device is comparable to that of the present $LiNbO_3$ airgap devices. This device has the potential of having very large dynamic range because of the absence of spurious bulk wave generation, as occurs in the airgap device. Several signal processing functions have been demonstrated with this new type of storage correlator. In one chirp correlation experiment, correlation of signals with a time-bandwidth product of 4000 has been observed.

*This work was supported by the Office of Naval Research under contract N00014-76-C-0129.

Because of its wide applications as a signal processing device, the storage correlator has attracted much attention in the past two years.[1,2,3] All the storage correlators with diode arrays that have been fabricated so far are of the so-called airgap type, where a substrate of silicon with diode array on it is separated by an airgap from a $LiNbO_3$ delay line. In order to achieve efficient and uniform interaction between the acoustic wave and the diode array, sophisticated assembly techniques have to be used to maintain a thin airgap typically of the order of 2000 Å along the whole length of the diode array. This requires that each device be assembled and adjusted individually. For this reason and others to be explained later, a monolithic structure is desirable.

In this paper we describe such a monolithic storage correlator. The configuration of the device is schematically shown in Fig. 1. This configuration is very similar to that of the zinc-oxide-on-silicon convolver demonstrated by Khuri-Yakub and Kino.[4] A zinc oxide layer 1.6 μm thick is rf-sputtered on the Si substrate to provide the piezoelectric coupling between the acoustic surface wave and the silicon. The rf power used for the deposition is 160 watts and the Si substrate is kept at 250° C throughout the sputtering process. The oriented gold pads at each end of the delay line provide slightly better underlayers than SiO_2 for the zinc oxide growth. These pads also act as ground planes for the interdigital transducers which are deposited on top of the ZnO layer on the gold pads. The 10 finger interdigital transducer is designed to launch a 1-mm-wide acoustic beam at 125 MHz center frequency. The n-type (111) Si substrate used has a resistivity of 9-15 Ω-cm . The p^+-n diodes on the surface of the Si substrate are 4 μm wide with 4 μm spacing

between diodes. These diodes are fabricated by shallow boron diffusion ($\approx 0.6\ \mu m$) following a n^+ gettering phosphorus diffusion on the back of the Si wafer. This gettering process reduces the number of metallic ions present at the Si surface, thus diodes with low leakage current can be fabricated reproducibly.

Simple inductance tuning for the two transducers yields a terminal-to-terminal loss of about 19 db with a 3 db bandwidth of 8 MHz . When used as a convolver, this device gives an overall convolution efficiency of -66 dbm . Considering the fact that the diodes occupy only half the area of the active silicon region, this number compares favorably with -58 dbm as predicted and measured by Khuri-Yakub and Kino[4] for their zinc oxide convolvers.

Several modes of operation are possible when this device is used as a storage correlator. In the present case, the writing process is accomplished by storing a charge pattern in the diode array through the simultaneous presence of an rf signal applied to the top plate and the electric fields associated with the acoustic signal launched by transducer A . After the storage interval, by applying another rf signal to the top plate, the correlation of this signal with the stored signal is obtained at the acoustic port B . In this mode of operation we have observed 65 db output dynamic range with a 3 db storage time of 20 msec or more, with the maximum acoustic input level of 26 dbm at the acoustic port and 6 v p-p at the input terminal of the top plate both for write in and read out.

It is important to note that due to the presence of the rf signal on the top plate during read-out, spurious signals will be detected along with the

correlation output. These spurious outputs are caused either by direct rf pick-up by the output port or by the surface wave and/or bulk wave generation when the piezoelectric zinc oxide film is excited by the top plate rf signal. The direct rf feedthrough has been reduced below the thermal noise of the measuring system by extremely careful design of the enclosing metal box and by properly grounding the silicon substrate.

Since the piezoelectric zinc oxide film on our device is only 1.6 μm thick, bulk wave generation by the read out signal which severely limits the input dynamic range of the airgap storage correlator is not present; this is a major advantage. Therefore, our main concern is with spurous surface wave generation either from the ends of the top plate or from the whole length of the active zinc oxide film underneath the top plate. By slanting the ends of the top plate; the former effect has been eliminated. The spurious surface wave generation by the whole active region underneath the top plate at the present time limits the input dynamic range of our device to 30-35 dbs ; i.e., the range over which the level of the signal to be stored can be varied during the write-in process before the correlation output drops to the spurious signal level.

Our present hypothesis for the cause of this spurious signal is that the diode array perturbs the surface waves. Therefore, any structural periodicity appearing in the diode array which matches the wavelength of the rf signals used can cause surface wave generation. In support of this argument, we note that the level of the spurious signal can be affected by DC bias applied to the top plate which controls the surface potential of the n-type regions between diodes. Effort is under way at the present time to fabricate new devices with a simplified

array structure. Unfortunately, for historical reasons, the present diode elements are staggered giving an additional periodicity of 130 μm, which could cause the unwanted spurious surface wave generation through its 4th harmonics.

Several signal processing functions have been demonstrated with this device. Figure 2 shows the storage correlation of a 5-bit Barker code. The Barker code is stored in the diode array by feeding it to the top plate and at the same time passing a 200 nsec acoustic pulse underneath it. The side lobe level is within 2 db of the theoretical value of -14 db. A second experiment demonstrates that integration and correlation between two input signals can be obtained. Two identical linear FM chirps are inserted simultaneously into both the acoustic port and the top plate.[5] These signals are arranged to be of low enough level so that many rf cycles are required to saturate the diodes. In this case the device stores a component of charge which is proportional to the integral of the product of the two signals, i.e., if the signals are $F(t)\,e^{j\omega t}$ and $G(t)\,e^{j\omega t}$, respectively, the stored signal is

$$H(x) = \alpha \int F(t - x/v)\, G(t) \cos \omega x/v \, dt$$

where α is a constant and v the acoustic wave velocity. By delaying one chirp by 3 μsec with respect to the other we obtain the stored correlation peak of the two chirps in a short region along the diode array. Thus the long chirp is compressed into a narrow charge spike stored in the diode array. The compression ratio depends on the time-bandwidth product of the chirp used which in turn is only limited by the bandwidth and storage time of the device.

Since the storage time of the device can be very long (a few hundred msec or more) extremely large compression ratios can be achieved.

Trace (a) of Fig. 3 shows the correlation output obtained with short pulsed readout signal of approximately 100 nsec. It will be observed that the output is 200 nsec wide, when the input FM chirp is 700 μsec long and has a frequency excursion of 6 MHz . This represents a compression ratio of about 3500. As a check on this result, we note with trace (b) that when the chirp is gated to 350 μsec long, thus reducing the bandwidth by a factor of two, the compressed output pulse widens by a factor of 2, and its amplitude drops; in addition the sidelobe levels become much worse - probably due to the fact that this device is as yet not a true linear integrator. As demonstrated by Ingebrigtsen and Stern[6] we believe that it should be possible to operate the device in a linear integration mode. These experiments demonstrate that like the airgap storage correlator, this monolithic device stores both the amplitude and phase of a signal; and demonstrates that correlation of extremely large time-bandwidth product signals can be obtained.

We conclude that an efficient monolithic zinc-oxide-on-silicon storage correlator can be fabricated. Its capability and versatility as a signal processing device have been demonstrated. Because of the absence of spurious bulk wave generation, it may become a practical signal processing device offering large dynamic ranges, both at input and at output. In addition it offers the possibility of correlating signals with extremely large time-bandwidth products determined by the storage time of the device and the bandwidth of the transducers. As storage times can be a second or more and bandwidth in the tens of megahertz range, the possible signal processing capability is impressive.

ACKNOWLEDGEMENT

The authors wish to thank Dr. Khuri-Yakub for many valuable suggestions on the subject of ZnO technology and L. Goddard for his contributions to making the ZnO film growth a more reproducible process.

REFERENCES

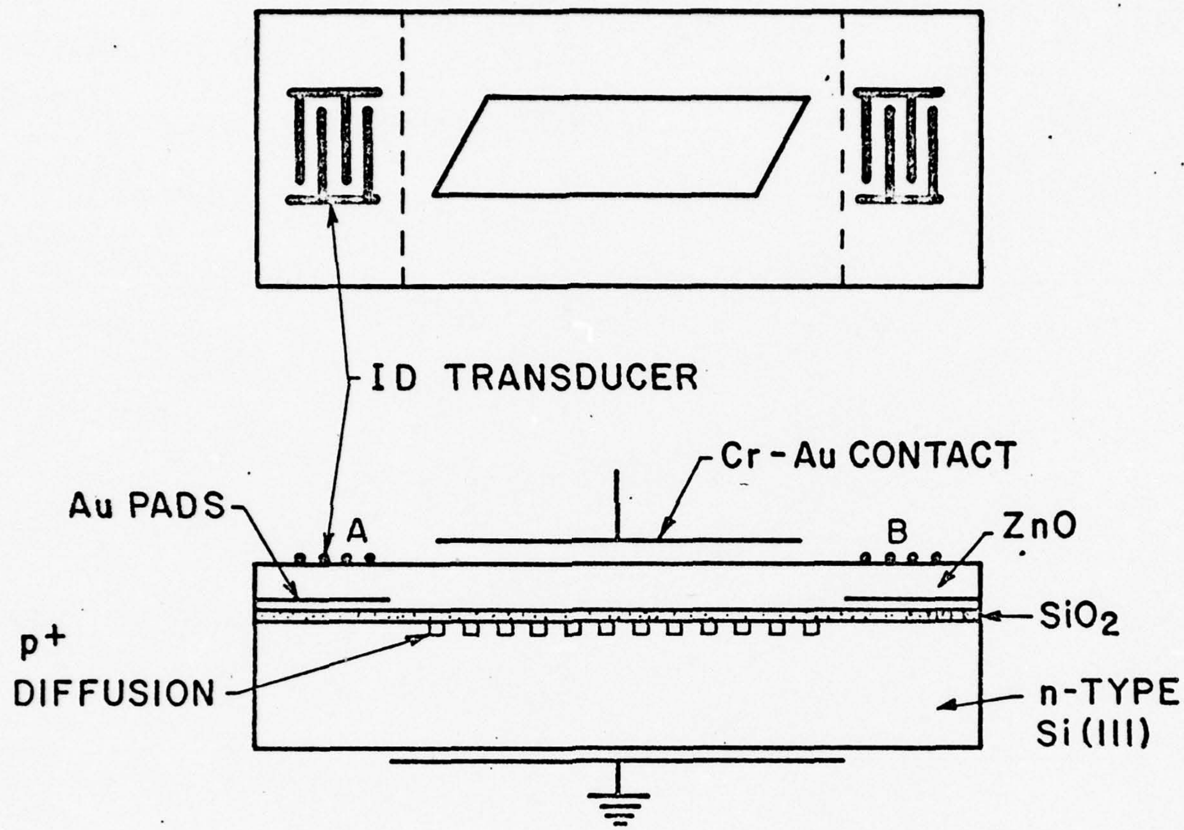
1. K. A. Ingebrigtsen, R. A. Cohn, and R. W. Mountain, Appl. Phys. Letters 26, 596-598 (1975).
2. C. Maerfeld, Ph. Defranoud, and P. Tournois, Appl. Phys. Letters 27, 577-578 (1975).
3. P. G. Borden and G. S. Kino, Appl. Phys. Letters 29, 527-529 (1976).
4. B. T. Khuri-Yakub and G. S. Kino, Appl. Phys. Letters 25, 188-190 (1974).
5. P. G. Borden and G. S. Kino, "Input Correlation with the ASW Storage Correlator," G. L. Report No. 2715, Stanford University.
6. K. A. Ingebrigtsen and E. Stern, Appl. Phys. Letters 27, 170-172 (1975).

FIGURE CAPTIONS

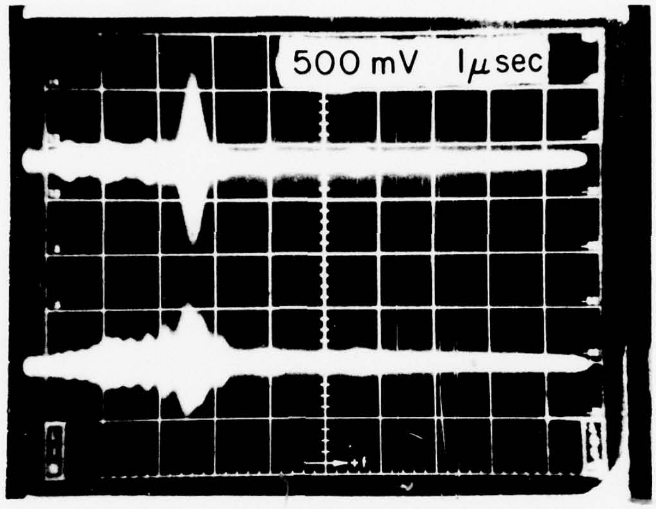
Fig. 1--Schematic of the zinc-oxide-on-silicon monolithic storage correlator.

Fig. 2--Storage correlation of 5-bit Barker code. (Horizontal: 2 μsec/div)

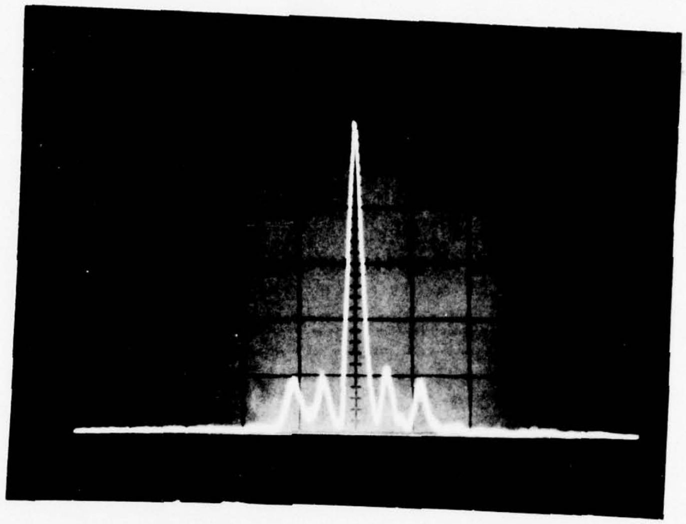
Fig. 3--Correlation peak obtained with (a) 700 μsec, 6 MHz (b) 350 μsec, 3 MHz linear FM chirps.



Schematic of zinc-oxide-on-silicon monolithic storage correlator.



Correlation peak obtained with (a) 700 sec, 6 MHz (b) 350 sec, 3 MHz linear FM chirps.



Storage correlation of 5-bit Barker code.

THE CHARGING PROCESS IN THE ACOUSTIC SURFACE WAVE P-N DIODE STORAGE* CORRELATOR

by

P. Borden
G.S. Kino

ABSTRACT

We demonstrate analytically and experimentally that the acoustic surface wave p-n diode storage correlator may be charged either very quickly or very slowly, depending on the input signal levels, and independent of the diode storage time.

Thus, the same long storage time device is usable for both high speed and slow (such as integrating) applications.

*The work reported in this paper was supported by the Office of Naval Research under grant N00014-76-C-0129 and The National Science Foundation under grant NSF ENG75-18681.

Storage correlators employing both Schottky[1] and p-n[2,3] diodes have been demonstrated. The relationship between the charging and storage processes has not been well understood, and it has been generally assumed that devices exhibiting long storage times will require long charging times. We have theoretically and experimentally demonstrated that this is not so. Charging time depends mainly on the input levels; thus, even long storage time p-n diodes may be charged during periods adjustable from a nanosecond to a second or longer.

The storage correlator configuration is shown in Fig. 1A, with corresponding equivalent circuits in Figs. 1B and 1C. An array of p-n diodes fabricated on a semiconductor interacts with a surface wave traveling on a neighboring substrate. In the charging process, a short pulse applied to the diode array switches each diode on. The capacitor charges up to a voltage corresponding to that of the pulse (Fig. 1B). When the pulse amplitude drops to zero, the capacitor remains charged and the diode becomes reverse biased, so that stored charge is slowly lost through the diode leakage current. In actual operation, the diode voltage is the sum of two terms one due to the acoustic surface wave and the other due to the pulse. After charging, the reverse biased diodes act like varactors, their capacities depending on the stored charge. If a later signal is applied to the array, it will excite a potential on the piezoelectric substrate whose amplitude depends on the diode capacities. By this means, the stored charge may be read out.

In another paper, we present a complete theory of this operation. Here we only discuss the diode charging and show that, although p-n diodes are reputed to be slow, it is indeed possible to read signals into these diodes

in nanosecond intervals, independent of the storage time. Furthermore, by employing smaller potentials, it is possible to charge relatively slowly in an integrating mode.

To understand the charging process, we consider the action of switching on the diode by accounting for its transient response. To do this, we first consider the case of charging with a single short pulse (Fig. 1B). By solving the p^+-n junction diffusion equation for times much shorter than the hole recombination time, we can show that the diode voltage V_D is

$$V_D(t) = \frac{kT}{q} \ln \left[1 + \frac{1}{p_{n0}\sqrt{\pi D_p}} \int_o^t \frac{J(\tau)}{(t-\tau)^{1/2}} d\tau \right] \qquad (1)$$

where the current density at a time τ is $J(\tau) = -qD_p \frac{\partial p}{\partial x}$ and $p(x = 0, t) = p_{n0}\left(e^{qV_D/kT} - 1\right)$. D_p is the diffusion constant for holes, q the electronic charge and p_{n0} the minority carrier density in the n layer in thermal equilibrium. We assume that the diode is charged through a capacitor C with a pulse of the form $V(t) = V_0\left[1 - \frac{(t-t_0)^2}{t_0^2}\right]$, as in Fig. 1B. Then if the conduction current through the diode is much larger than the displacement current, the current varies linearly in time. It follows from Eq. (1) that the diode voltage is

$$V_D(t) = \frac{kT}{q} \ln \left[1 + \frac{4CV_0 \sqrt{t}}{qp_{n0}t_0 \sqrt{\pi D_p}} \left(1 - \frac{3t}{2t_0}\right)\right] \qquad (2)$$

At $t = 3/2\, t_0$, when $V = 3/4\, V_0$, the diode becomes reverse biased, and, hence, 3/4 of the peak charge in the capacitor C is stored. Successive pulses will asymptotically increase the stored charge to the maximum value CV_0 .

A second case is when relatively weak signals are used to charge the diodes. Now the capacitive current of the diode dominates and the circuit model of Fig. 1C is appropriate. Here we solve the diffusion equation for a sinusoidal voltage excitation to find the diode current. The charge in the capacitor, due to this current, increases logarithmically in time as:

$$Q(t) = \frac{kT}{q} C_D \ln \left[1 + \frac{q^2 P_{n0} t}{kTC_D} e^{\frac{q}{kt} V_0 \frac{C}{C + C_D}} \sqrt{\frac{kT\omega D_p}{3\pi q V_0} \frac{C + C_D}{C}} \right] \tag{3}$$

where ω is the frequency and $C_D = \sqrt{\dfrac{2qN_D\epsilon_S}{V_B - V_D}}$ is the diode capacitance, taken to be constant, V_B is the built in diode voltage, and V_D is taken at its maximum value in defining the capacitance.

The readout signal received at either acoustic port is a result of the read in of a small rf signal $\varphi_a \exp j\omega t$ on a transducer and a signal $\varphi_p \exp j\omega t$ on the plate. Assuming that the dominant potential at the diode is due to φ_p , it is as if the applied potential V_A is of the form

$$V_A = \left[A\varphi_p + B\varphi_a \right] \exp\left(- j\omega x / v \right) \tag{4}$$

where A , B , are constants and v is the acoustic velocity.

Inserting this result in Eq. (3), we can show that there will be a stored component of charge with a spatial wave number $k = \omega/v$, which varies as $\varphi_p \ell n(Kt)$ where K is a constant.

The significant results of this analysis are twofold:

(1) The diodes can be charged to 75% of the maximum value with a single pulse of sufficient amplitude and duration less than 1/2 rf cycle.

(2) For small amplitude pulses, the stored charge varies logarithmically with time. Thus, the charging rate can be very low.

We have performed experiments to verify these results. The device employed a mesa p-n diode array[5] with a room temperature storage time of 35 msec. The frequency was 108 MHz and the charging pulse length was ~ 5 nsec. While the storage time varied by more than three orders of magnitude, the charging characteristics remained almost constant over a 64°C temperature range as shown in Fig. 2. This is expected from Eq. (2) since $n_i \propto T^{3/2} \exp [E_g/2kT]$, and V_D is virtually independent of T. This proves that a very long storage time diode can be charged with a very short pulse of sufficient amplitude.

The same device can also exhibit slow charging characteristics under the proper conditions; i.e., with small amplitude charging signals. In Fig. 3 a plot of the device output is given as a function of the logarithm of the charging time. The output and output slope both vary as $\varphi_p \ell nt$, as predicted in the discussion following Eq. (3).

The logarithmic charging behavior has been observed in earlier experiments. Such observations were interpreted to show that long storage time diodes will exhibit slow charging characteristics. The present work indicates that those results were due to the low levels of the charging signals, and not to any inherent physical limitations of the diodes.

To conclude: through the proper choice of input signal levels, the charging time may be varied from a few nanoseconds or less to a second or more. Furthermore, this behavior will be independent of the diode storage time.

REFERENCES

1. K. A. Ingebrigtsen, R. A. Cohen, and R. W. Mountain, "A Schottky-Diode Acoustic Memory and Correlator," Appl. Phys. Letters, Vol. 26, pp. 596-598, June 1975.

2. C. Maerfeld, P. Defranould, and P. Tournois, "An Acoustic Storage and Processing Device Using PN-Diodes," Appl. Phys. Letters, Vol. 27, pp. 577-578, 578, December 1975.

3. P. G. Borden and G. S. Kino, "Correlation with the Storage Convolver," Appl. Phys. Lett., Vol. 29, pp. 527-529, November 1976.

4. P. G. Borden and G. S. Kino, to be published.

5. R. Joly, "A Mesa P-N Diode Array Acoustic Surface Wave Convolver," Appl. Phys. Letters, Vol. 29, pp. 525-527, November 1976.

6. P. Defranould, H. Gautier, C. Maerfeld, and P. Tournois, "PN Diode Memory Correlator," Ultrasonics Symposium Proceedings, pp. 336-347, September 1976.

FIGURE CAPTIONS

Fig. 1 -- (a) Storage correlator configuration and operation.

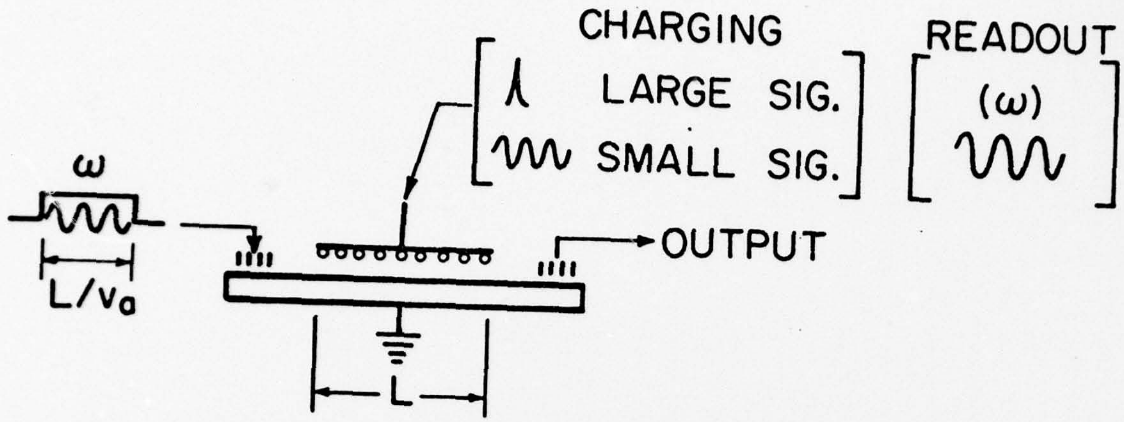
(b) Charging model for a single large pulse.

(c) Charging model for a small signal.

Fig. 2 -- Correlation output as a function of the amplitude of the charging pulse over a $64^{o}C$ temperature range.

Fig. 3 -- Correlation output as a function of the charging time and rf input voltage φ_p .

(a)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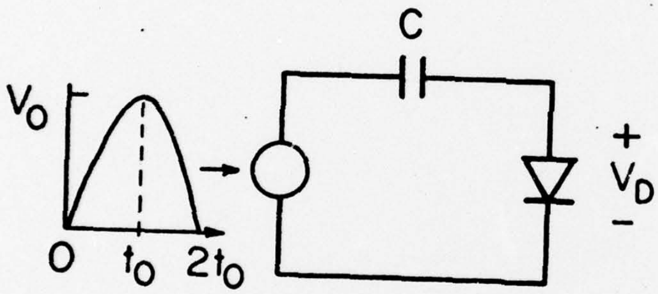
(b)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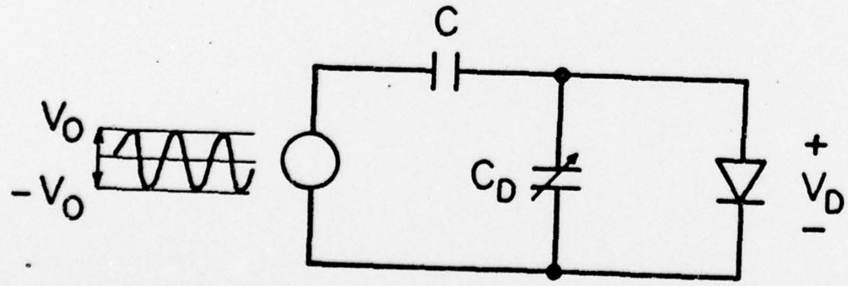
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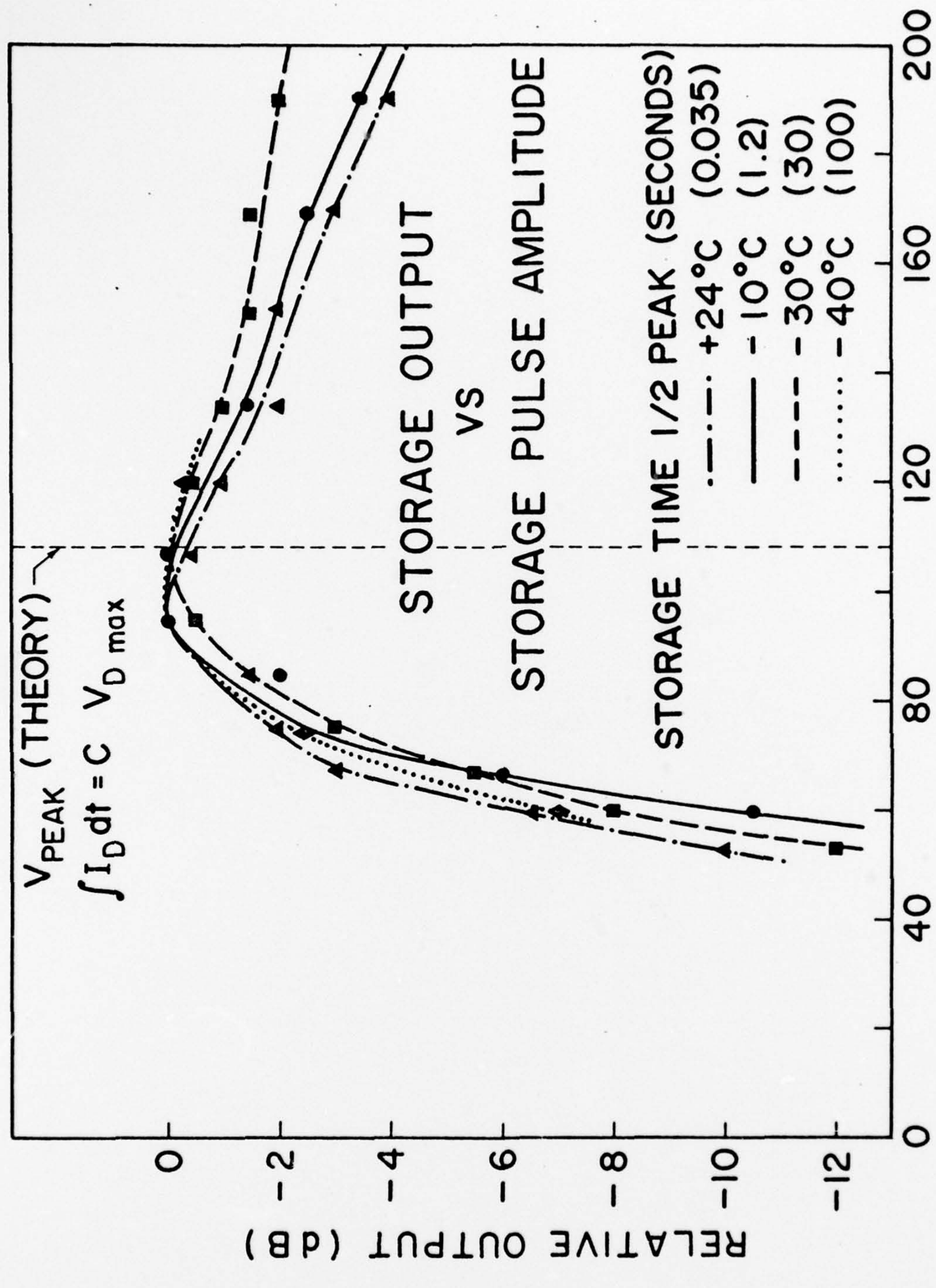

V_PEAK (THEORY)
∫I_D dt = C V_D max
STORAGE OUTPUT
VS
STORAGE PULSE AMPLITUDE
STORAGE TIME 1/2 PEAK (SECONDS)
+24°C (0.035)
-10°C (1.2)
-30°C (30)
-40°C (100)
RELATIVE OUTPUT (dB)
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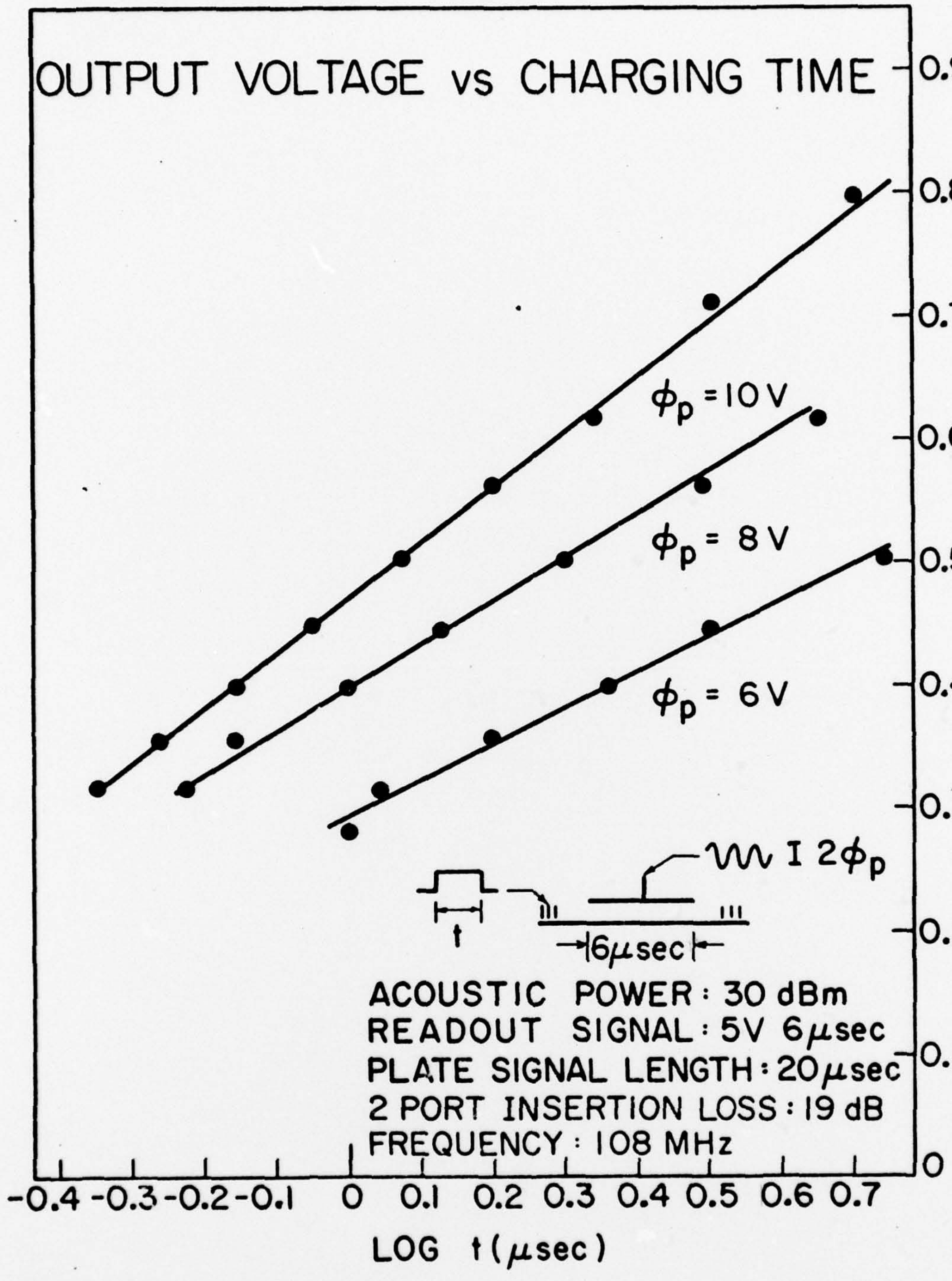

OUTPUT VOLTAGE vs CHARGING TIME
ϕ_p = 10 V
ϕ_p = 8 V
ϕ_p = 6 V
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t
6μsec
ACOUSTIC POWER : 30 dBm
READOUT SIGNAL : 5V 6μsec
PLATE SIGNAL LENGTH : 20μsec
2 PORT INSERTION LOSS : 19 dB
FREQUENCY : 108 MHz
-0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
LOG t (μsec)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
V OUT (RELATIVE SCALE)

INPUT CORRELATION WITH THE ASW STORAGE CORRELATOR

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ABSTRACT

By correlating during readin, we correlate signals of much greater length than could be stored within the device, thereby obtaining a large improvement in TB product.

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INPUT CORRELATION WITH THE ASW STORAGE CORRELATOR

The acoustic surface wave storage (or memory) correlator has recently received considerable attention as a high bandwidth signal processor.[1] We here consider a new mode of device operation that affords greatly increased time-bandwidth product; namely, input correlation.

The device consists of a pn junction diode array situated above a piezoelectric surface wave delay line. Fig. 1a shows a typical mode of operation whereby the modulation $W(t)$ of a signal $W(t)e^{j\omega t}$ is written into the diode array as a stored charge pattern and read out at some later time as a correlation with a reading signal $R(t)e^{j\omega t}$.

The writing process involves the interaction of two rf inputs. We first consider the case where one is used to excite a short acoustic surface wave pulse and the other is applied to the diode array through a capacitor, the capacity between the diode array and the ground electrode on the other side of the delay line. Thus, the source in Fig. 1c is of the form $V_s = Se^{j(\omega t-kz)}+W(t)e^{j\omega t}$, where S is a constant. The surface wave term is assumed to be dominant, but still of insufficient strength to allow the diode conduction current to exceed its displacement current. Thus, the voltage divider consisting of C and the diode depletion layer capacitor, C_D, determines the diode voltage V_D. During successive peaks of the surface wave potential, small amounts of forward diode current flow. This puts successive increments of change into the capacitor C, due to both S and $W(t)$.

After the surface wave pulse passes by the diode $V_s \simeq 0$, so that the capacitor C is placed across the diode, reverse biasing it. The stored charge now leaks out slowly through the diode reverse current. The reverse biased diode acts like a varactor whose capacity depends

on the stored charge. A readout signal $R(t)e^{j\omega t}$ applied to the diode array excites a surface wave whose amplitude depends on the diode capacities. This wave appears at the transducer opposite the one used for input as the correlation of R and the stored charge pattern.

By solving the p^+n diode diffusion equation for times much shorter than the minority carrier recombination time, we can show that the diode neutral region charge increases logarithmically in time during the charging process as[2]:

$$Q(t) = \frac{kT}{q} C_D \ln\left[1 + \frac{q^2 p_{no} t}{\pi kT C_D}\sqrt{\frac{\omega D_p kT}{3\pi qS}\frac{C + C_D}{C}} \exp\left(\frac{qS}{kT}\frac{C}{C + C_D}\right)\right]$$

where S is the peak surface wave potential, $C_D = \sqrt{\frac{2qN_D C_s}{(V_B - V_D)}}$ is taken at the peak value of V_D, p_{no} is the thermal equilibrium minority carrier concentration, D_p is the minority carrier diffusion constant, N_D is the doping density, and ω is the frequency.

Since $V_D(z,t)$ has some dc component V_o, a pure rf component $W(t)e^{j\omega t}$, and a component due to the surface wave $S(z,t)e^{j(\omega t - kz)}$, expansion of the above equation yields a product term of the form $WSe^{jkz}\ln(Bt)$, where B is constant. The logarithmic characteristic allows charge to be integrated over long intervals by appropriate choice of the input levels. Because this component of charge varies with the product of the two input signals, it is also possible to correlate two long input signals during the charging process. At the present time, unless S is carefully chosen so as to use only a linear portion of the charging characteristics, the non-linear time dependence makes this technique poorly suited for amplitude dependent correlations. It would, nevertheless be of considerable use in phase sensitive correlations, such as those performed with FM chirps. Modifications can, however, be performed to charge linearly from a current source, as described by Ingebrigtsen[3].

The TB product is normally limited by the transducer bandwidth and diode array length. Input correlation allows correlation of signals much longer than could normally be stored, yielding a corresponding increase in TB product. For example, the longest convolver so far constructed covers a 35 μsec. signal in its 12.1 cm. length[4]. By careful adjustment of signal levels, input correlation should allow correlation of signals $\gtrapprox 1$ msec. long, yielding a TB improvement of at least 30, and, in certain applications, obviating the need for a long diode array.

We have experimentally demonstrated this by input correlating two linear FM chirps. Fig. 2a shows the experimental setup. The plate chirp is a delayed replica of the acoustic chirp, so that the plate and surface wave frequencies will match near one point along the diode array. A correlation peak will be stored there, which may be directly read out at some later time.

Our device had a center frequency of 105.5 MHz and a 3 dB bandwidth of about 7 MHz. The mesa p^+n diode array length was 2 cm (6 μsec). The acoustic and plate inputs were both 40 μsec, 7.3 MHz linear FM chirps with a center frequency of 105.4 MHz. To obtain the plate delay, a common chirp was generated and mixed up in frequency before being applied after a 60 μsec. delay. Both plate signal amplitudes were 8 V 0-p. The acoustic signal was 23.5 dBm and the minimum 2-port delay line loss was 18.5 dB at 106 MHz.

The correlation output is seen in Fig. 2b. The width at half maximum is 180 nsec., corresponding to a compression ratio over the original 40 μsec. inputs of 220. The theoretical compression, corresponding to the TB product, is 40 μsec. X 7.3 MHz = 292. It should be noted that the observed output is actually the correlation of the 50 nsec readout pulse with the stored charge pattern, thus broadening the output about 10% over the true correlation charge pattern. Nevertheless, the performance improvement is dramatic. In the output correlation mode, the peak compression obtainable is limited by the diode array length and transducer bandwidth to about 6 μsec. X 7.3 MHz = 44, or about 20% of that obtained through input correlation.

Thus, input correlation removes the TB limit imposed by the finite diode array length. The technology required to correlate certain extremely long signals then becomes far simpler, allowing extremely high TB signal processing with the storage correlator.

REFERENCES

1. INGEBRIGTSEN, K.A.: "The Schottky Diode Acoustoelectric Memory and Correlator: A novel programmable signal processor." Proc. IEEE, 1976, 64,(5). pgs. 764-769.

2. BORDEN, P., and KINO, G.S.: "An Analytic Theory of the Storage Correlator," to be published.

3. INGEBRIGTSEN, K.A. and STERN, E.: "Coherent Integration and Correlation in a Modified Acoustoelectric Memory Correlator," Appl. Phys. Lett., 1975, 27, (4), pgs. 170-172.

4. REIBLE, S.A., CAFARELLA, J.H., RALSTON, R.W., STERN, E.: "Convolvers, for DPSK Demodulation of Spread Spectrum Signals", Proc. IEEE SU Symposium, 1976, pgs. 451-455.

CAPTIONS

Fig. 1a: (a) A typical mode for storage and output correlation.
(b) Input correlation and readout.
(c) Equivalent circuit model.

Fig. 2 (a) Input correlation experimental setup.
(b) Correlation output.

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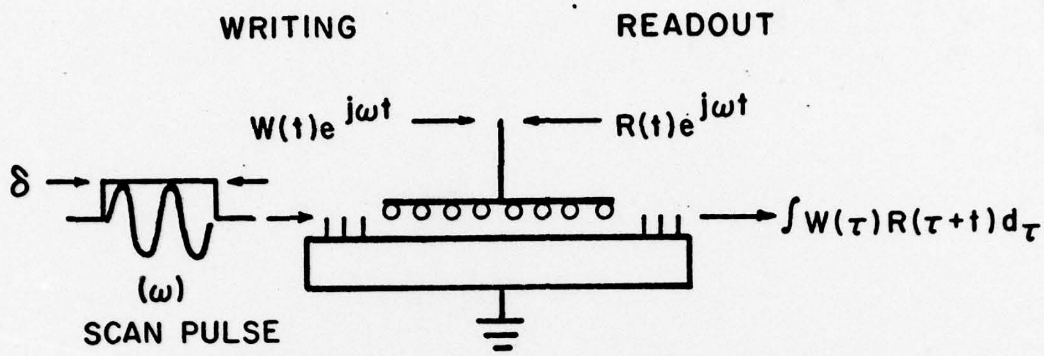
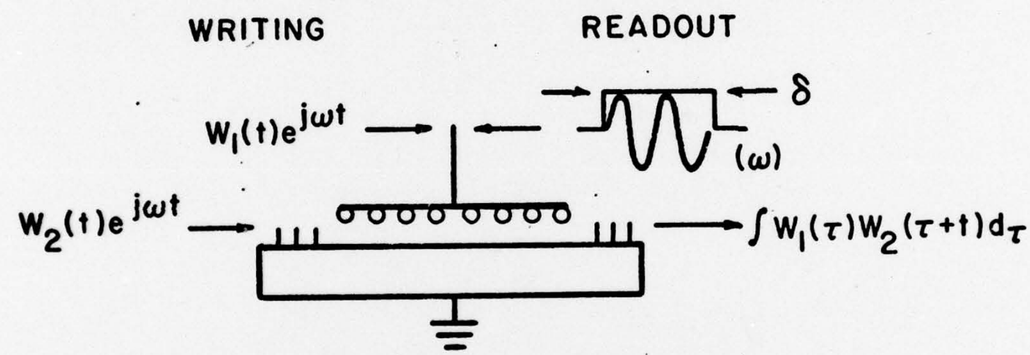
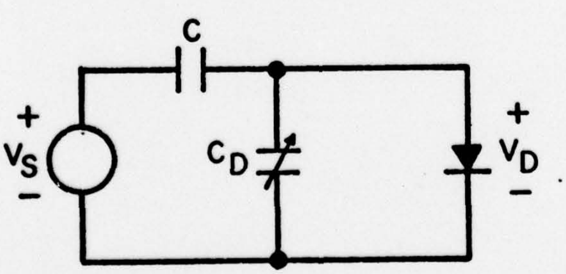

WRITING
READOUT
$W(t)e^{j\omega t}$
$R(t)e^{j\omega t}$
δ
$\int W(\tau)R(\tau+t)d\tau$
(ω)
SCAN PULSE

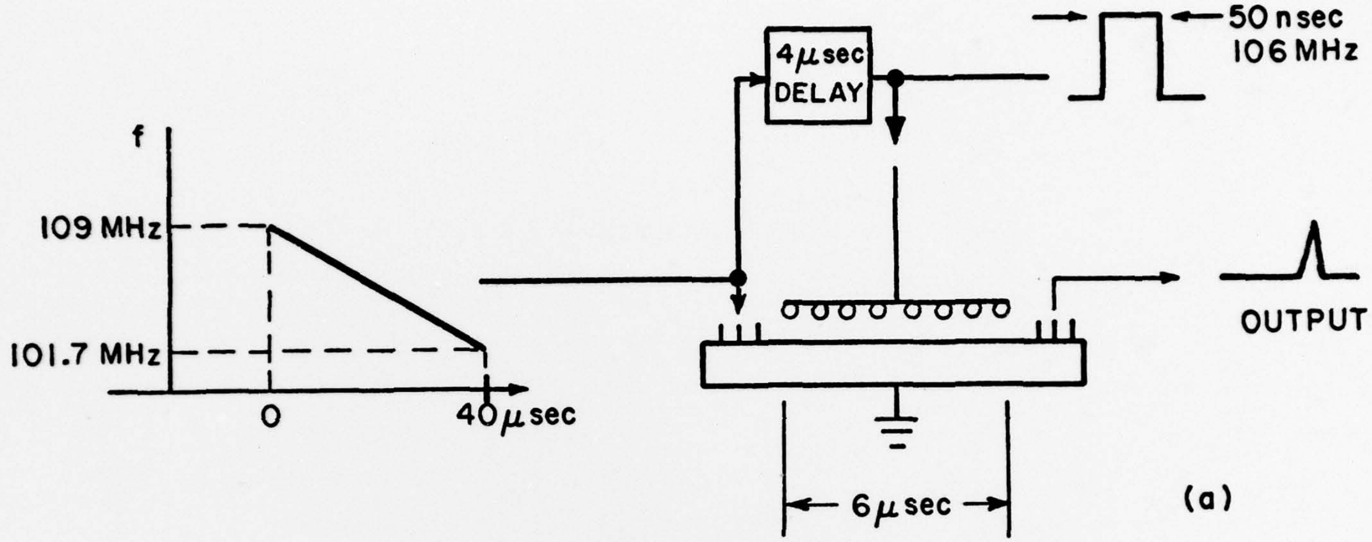
(a)


WRITING
READOUT
δ
$W_1(t)e^{j\omega t}$
(ω)
$W_2(t)e^{j\omega t}$
$\int W_1(\tau)W_2(\tau+t)d\tau$

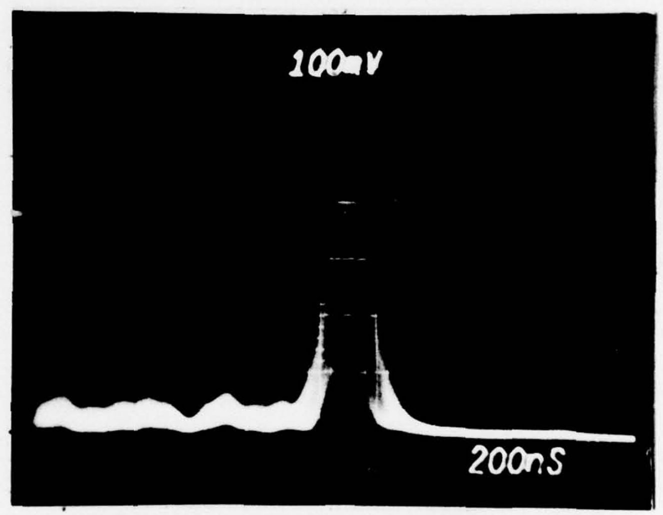
(b)


C
+
V_S
−
C_D
+
V_D
−

(c)


f
109 MHz
101.7 MHz
0
40 μsec
4 μsec DELAY
50 nsec
106 MHz
OUTPUT
6 μsec

(a)


100mV
200nS

(b)